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A Climate-Change Scenario for the Columbia River Basin

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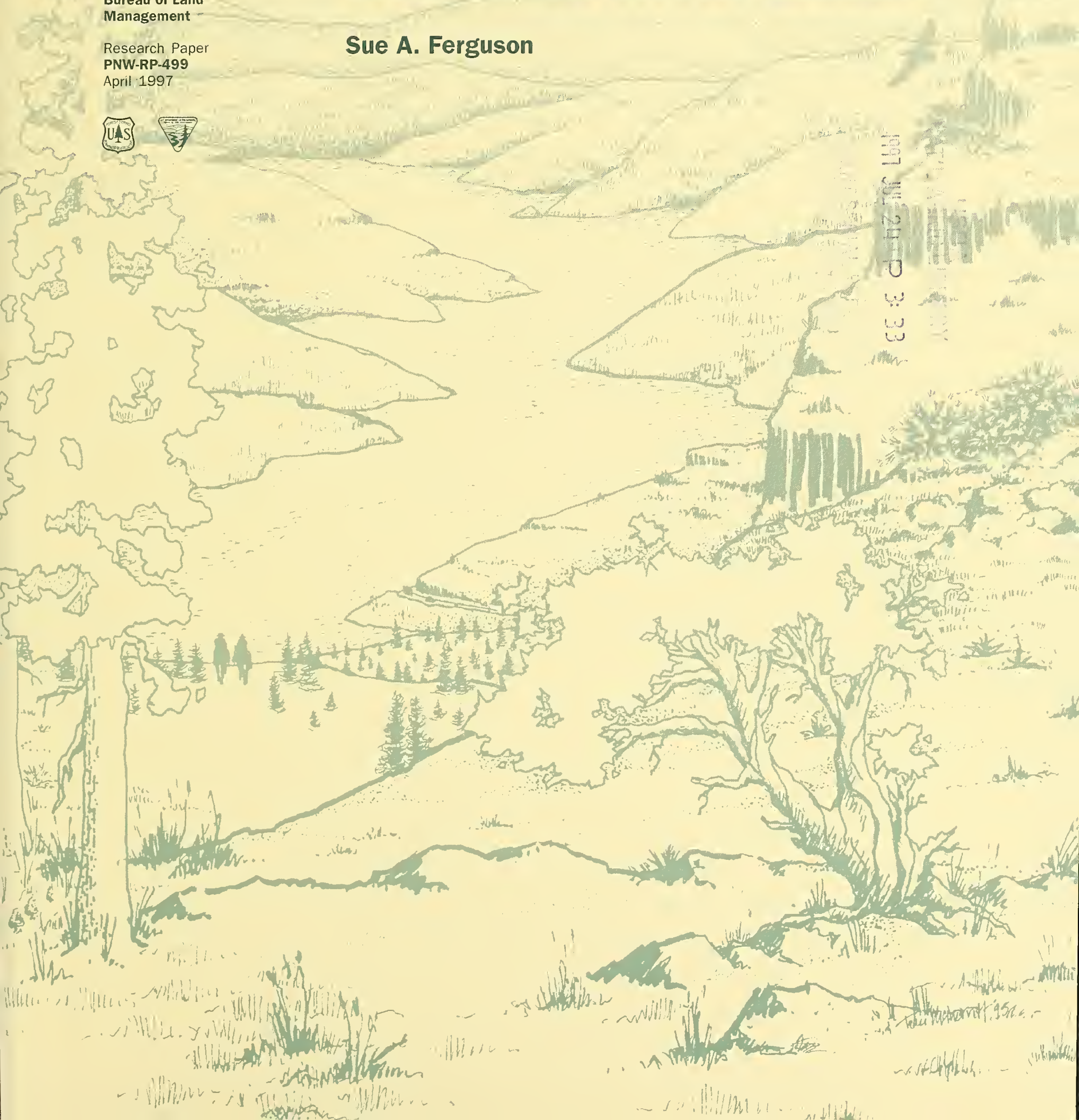
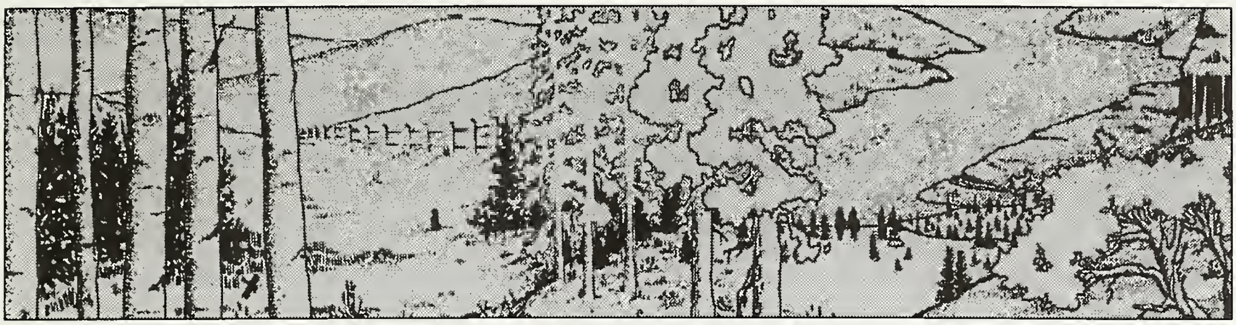


Author

SUE A. FERGUSON is an atmospheric scientist, Forestry Sciences Laboratory, 4043 Roosevelt Way NE, Seattle, WA 98105.



A Climate-Change Scenario for the Columbia River Basin

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Interior Columbia Basin Ecosystem Management Project: Scientific Assessment

Thomas M. Quigley, Editor

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Abstract

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This work describes the method used to generate a climate-change scenario for the Columbia River basin. The scenario considers climate patterns that may change if the atmospheric concentration of carbon dioxide (CO_2), or its greenhouse gas equivalent, were to double over pre-Industrial Revolution values. Given the current rate of increase in atmospheric CO_2 concentration, doubling could occur within the next 50 to 100 years.

The Columbia River basin is in a transition climate zone between predominating maritime to the west, arctic to the north, and continental to the east. Consequently, it is difficult to characterize through means and averages. Therefore, many of the current stochastic methods for developing climate-change scenarios cannot directly apply to the basin. To circumvent this problem, a composite approach was taken to generate a climate scenario that considers knowledge of current regional climate controls, available output from general circulation and regional climate models, and observed changes in climate.

The resulting climate-change scenario suggests that precipitation could increase substantially during winter (+20 to +50 percent) and moderately during spring and autumn (+5 to +35 percent). A slight decrease (0 to -5 percent) in summer precipitation is possible, except for the southeastern portions of the basin that may experience an increase in convective precipitation (+5 percent).

Low-elevation (<1 kilometer) temperatures throughout the year may increase 1 to 3 °C, with greatest increases during winter. This amount of temperature change is possible because of an expected loss of low-elevation snow cover. At high elevations, increased cloud cover could cause average temperatures to decrease during winter but be synchronized with possible warming at low elevations during summer. The diurnal range of temperature could decrease, especially in summer and autumn.

Keywords: Climate, climate change, climate scenario, Columbia River basin, Pacific Northwest, global warming, general circulation model, regional climate model, global change, global climate, greenhouse gas.

Preface

The Interior Columbia Basin Ecosystem Management Project was initiated by the Forest Service and the Bureau of Land Management to respond to several critical issues including, but not limited to, forest and rangeland health, anadromous fish concerns, terrestrial species viability concerns, and the recent decline in traditional commodity flows. The charter given to the project was to develop a scientifically sound, ecosystem-based strategy for managing the lands of the interior Columbia River basin administered by the Forest Service and the Bureau of Land Management. The Science Integration Team was organized to develop a framework for ecosystem management, an assessment of the socioeconomic and biophysical systems in the basin, and an evaluation of alternative management strategies. This paper is one in a series of papers developed as background material for the framework, assessment, or evaluation of alternatives. It provides more detail than was possible to disclose directly in the primary documents.

The Science Integration Team, although organized functionally, worked hard at integrating the approaches, analyses, and conclusions. It is the collective effort of team members that provides depth and understanding to the work of the project. The Science Integration Team leadership included deputy team leaders Russel Graham and Sylvia Arbelbide; landscape ecology—Wendel Hann, Paul Hessburg, and Mark Jensen; aquatic—Jim Sedell, Kris Lee, Danny Lee, Jack Williams, Lynn Decker; economic—Richard Haynes, Amy Horne, and Nick Reyna; social science—Jim Burchfield, Steve McCool, and Jon Bumstead; terrestrial—Bruce Marcot, Kurt Nelson, John Lehmkuhl, Richard Holthausen, and Randy Hickenbottom; spatial analysis—Becky Gravenmier, John Steffenson, and Andy Wilson.

Thomas M. Quigley
Editor

United States Department of Agriculture

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Interior Columbia Basin Ecosystem Management Project

Summary

This work describes the method used to generate a climate-change scenario for the Columbia River Basin Ecosystem Management Project, which began in 1993. The project required an estimate of potential climate change to complement various scenarios of management alternatives. The scenario considers climate patterns that may change if the atmospheric concentration of carbon dioxide (CO_2), or its greenhouse gas equivalent, were to double over pre-Industrial Revolution values. Given the current rate of increase in atmospheric CO_2 concentration, doubling could occur within the next 50 to 100 years.

The Columbia River basin is in a transition climate zone between predominating maritime to the west, arctic to the north, and continental to the east. Consequently, it is difficult to characterize through means and averages. Therefore, many of the current stochastic methods for developing climate-change scenarios cannot directly apply to the basin. To circumvent this problem, a composite approach was taken to generate a climate scenario that considers knowledge of current regional climate controls, available output from general circulation and regional climate models, and observed changes in climate.

The resulting climate-change scenario suggests that precipitation could increase substantially during winter (+20 to +50 percent) and moderately during spring and autumn (+5 to +35 percent). A slight decrease (0 to -5 percent) in summer precipitation is possible, except for the southeastern portions of the basin that may experience an increase in convective precipitation (+5 percent).

Low-elevation (<1 kilometer) temperatures throughout the year may increase 1 to 3 °C, with greatest increases during winter. This amount of temperature change is possible because of an expected loss of low-elevation snow cover. Warm temperatures and lack of low-elevation snow could reduce the magnitude of rain-on-snow floods. Wildfire potential could increase, however, as spring runoff from snowmelt is reduced. At high elevations, increased cloud cover could cause average temperatures to decrease during winter but be synchronized with possible warming at low elevations during summer. The diurnal range of temperature could decrease, especially in summer and autumn.

The degree of climate change is highly uncertain. Potential changes reported here, however, are unprecedented in human history. Also, if long-term changes are accompanied by changes in variability, the impact on ecosystem processes and climate-related disturbances could be significant. Therefore, it is important for resource managers to evaluate the effects of climate change on ecosystems in ways that will help plan for and adapt to potential impacts. Scenarios like this one can provide the basis for such analysis.

Introduction

This work describes the method used to generate a climate-change scenario for the Columbia River Basin Ecosystem Management Project, which began in 1993. The project required an estimate of potential climate change to complement various scenarios of management alternatives. There are many methods of generating climate scenarios that describe potential change in weather patterns. For example, analogues with historical or ancient climates, such as the drought of the 1930s or the last major ice age, which ended about 10,000 years ago, can be useful in learning how biological and physical systems respond to severe climate. Another method is to create scenarios that arbitrarily stress our environment; for instance, What would happen if a growing-season drought lasted 10 years? Some scenarios begin by altering aspects of our environment that are known to control large-scale flow patterns to see how the atmosphere will respond. "Nuclear-winter" models do this by blocking solar radiation (Cao and Liu 1992).

Recent concern about the influence of human activity on climate has promoted several scenarios that simulate the effects of increasing greenhouse gases (Houghton and others 1990, 1992, 1996), which help control temperatures in the lower part of Earth's atmosphere. This concern is prompted by a noticeable increase (about 0.5 percent per year since 1890) in atmospheric concentrations of carbon dioxide (CO_2) (Houghton and others 1990). Concentrations of other greenhouse gases (for example, methane, nitrous oxide, and chlorofluorocarbons) also have increased, but atmospheric (CO_2) concentration generally is used to demonstrate the effective greenhouse gas contribution.

If CO_2 were to continue to increase at its current rate, double the amount pre-Industrial Revolution levels may occur within the next 50 to 100 years. Many available climate scenarios are based on potential doubling of CO_2 and often are called $2xCO_2$ scenarios. Our current understanding of climate suggests that increasing greenhouse gases in this manner could raise surface temperatures (averaged over the globe) at a rate and magnitude that is unprecedented in human history. How these global changes will manifest themselves at a regional level is uncertain.

Because of the concern about increasing greenhouse gas concentrations and the availability of greenhouse gas scenarios, a $2xCO_2$ scenario was chosen for the Ecosystem Management Project. Many existing methods, however, for developing climate-change scenarios, which rely on large-scale patterns and mean conditions, cannot directly apply to the Columbia River basin (hereafter referred to as the basin). The basin is in a region of complex terrain with heterogeneous climate patterns. Frequent transitions between predominating maritime air to the west, arctic to the north, and continental to the east can cause abrupt changes. Therefore, to generate a reasonable scenario, a composite approach was taken that considers (1) knowledge of current regional climate controls, (2) available output from general circulation models and regional models, and (3) observed changes in climate.

Current Climate

The Columbia River basin is in a transition-type climate zone. It is influenced by three distinct air masses: (1) moist, marine air from the west that moderates seasonal temperatures; (2) continental air from the east and south, which is dry and cold in winter and hot with convective precipitation and lightning in summer; and (3) dry, arctic air from the north that brings cold air to the basin in winter and helps cool the basin in summer.

The timing and extent of competing air masses is controlled largely by synoptic weather patterns and local terrain features that differ across the basin. Prolonged periods of drought occur when Pacific storms are deflected around the region, thereby preventing the intrusion of moist, marine air. At these times dry, continental conditions prevail. Damaging frosts and freezing conditions commonly occur when arctic air invades the basin before winter hardening in autumn or after budbreak in spring. Cold damage also may occur in winter if a warm, marine intrusion is followed by a sweep of arctic air. In addition, the unique interplay among air mass types results in dramatic

changes during transition. The most unique of these transitions is rain-on-snow flooding that occurs when warm, wet marine air displaces cold, arctic conditions in winter. Lightning and gusty winds also occur during transitions between continental and marine air masses, mainly in spring and summer.

General Circulation Models

General circulation models (GCMs) are global atmospheric models that physically compute air movement caused by differential heating of Earth's surface and atmosphere, Earth's rotation, and topographic differences (especially among oceans, continents, and major mountain ranges). Such models have successfully reconstructed large-scale flow patterns of current climate (Houghton and others 1990, 1992, 1996). Therefore, there is some confidence in their ability to simulate the effect of $2xCO_2$.

Equilibrium GCMs

Equilibrium GCMs typically have a dynamic atmosphere with simple approximations for the hydrosphere, biosphere, and cryosphere. A change in conditions causes the system to respond almost immediately. Then reactions begin damping as the climate system moves toward a state of equilibrium, much like a volume of water that is dumped into a bucket; it sloshes violently around until settling into equilibrium with the bucket walls and gravity. Based on the output from several equilibrium GCMs, the best estimate for the increase of global-averaged, surface temperature under a $2xCO_2$ environment from equilibrium GCMs is 1.5 to 4.5 °C (Houghton and others 1990).

The following summarizes equilibrium GCM output as reported by the Intergovernmental Panel on Climate-Change in 1990 and 1992 (Houghton and others 1990 and 1992), roughly in order of confidence. Text in italics loosely interprets how such large-scale change may affect the basin climate:

1. Greatest warming over high-latitude continents: *less intense arctic influence during winter.*

2. Continents could warm more than oceans: *marine influence could remain similar but arctic and continental influences could warm.*

3. Decreased snow cover: *warmer winter temperatures where usual snow cover is absent and less intense temperature inversions, especially in the central basin.*

4. Increased convection over continents: *more summer lightning and more late-summer precipitation, especially in south and east portions of the basin.*

5. Decreased soil moisture during summer: *greater summer drought, especially in the central basin.*

6. Fewer, but stronger, winter cyclones: *less frequent but more significant disruption of basin air mass from marine influx.*

Despite confidence in the modeling ability of equilibrium GCMs, they cannot capture the dynamic feedback effects of oceans, seasonal changes in snow and ice cover, or green-up and dieback of vegetation with much accuracy. There remains a high degree of uncertainty, therefore, in GCM simulations of potential change. Newer models, which incorporate more dynamic components of the other environmental systems, have improved confidence. Often these are called coupled GCMs (CGCMs), or ocean-atmosphere GCMs (OAGCMs) because the main additions have been in ocean dynamics. Instead of modeling abrupt changes, like dumping water into a bucket, CGCMs can model transient, or time-dependent, responses like trickling water into a bucket. Most commonly, investigations of the dynamic response of oceans and atmospheres assume 1-percent-per-year increases in CO_2 concentration, or its greenhouse gas equivalent.

Transient CGCMs

Transient CGCMs show a slightly slower response to $2xCO_2$, especially in southern high latitudes and in the northern Atlantic Ocean where deep water is formed (Houghton and others 1992, 1996). All areas show unsteady climate change (that is, there will be periods of cooling during the next 50 to 100 years), but the general trend is expected to be toward a warmer global climate. Transient CGCMs calculate global-averaged temperature increases of 1.3 to 2.3 °C at the time of CO_2 doubling (60 to 100 years from present).

The spatial and temporal resolutions of GCMs and CGCMs are necessarily coarse. They require large amounts of computing power to run over the entire globe. Consequently, horizontal resolution of model grid cells usually are 500 to 1000 kilometers, about the size of the entire basin. This resolution allows a good approximation of long-wave patterns that are controlled by the relative position of continents and oceans. Regional patterns, which are controlled by mountains and other small-scale influences, are not well simulated by GCMs. Therefore, GCM output can provide only an estimate of large-scale changes in global circulation patterns.

Regional Climate Models

There are several ways to construct regional climate scenarios. One way is a direct application of potential change, which is calculated from differences between a GCM control run and $2xCO_2$ run, onto a baseline of local observation data that represents current climate (for example, Kittel and others 1995). It is assumed that the baseline data would retain the spatial heterogeneity in the observed climate. It also is assumed that changes would occur uniformly over the broad area that is the size of a GCM grid cell. Although the method is quick and relatively easy to apply, it has a chance of missing unique responses to climate change that occur at different elevations and over short horizontal distances in the basin.

Regional scenarios also may be constructed by using statistical downscaling techniques, where site observations are statistically related to large-scale averages or model-generated variables (Giorgi and Mearns 1991). These methods assume that the relations among variables in present-day conditions remain valid under a changed climate. In addition, long records of good-quality climate data are required. Good-quality observation data are scarce in mountainous regions of Western states, where most of the ecosystem management problems exist. Also, it is unclear whether statistical relations from one climate period can be applied to another, especially knowing that current climate in the basin is controlled by three competing air masses, each responding to climate change differently.

A third, more physical, way of constructing regional scenarios is to use the large-scale flow fields generated by GCMs as boundary conditions for a higher resolution mesoscale model (Giorgi and others 1992). This nested modeling approach assumes that both the GCM and mesoscale model are correct. At the time of this writing, only one regional model had been linked with a GCM to help estimate regional responses to $2xCO_2$ over the Pacific Northwest. The model, RegCM2, nests the Pennsylvania State University (PSU) and National Center for Atmospheric Research (NCAR) mesoscale model, MM4 (Anthes and others 1987), with the NCAR community climate model, (Williamson 1993, Williamson and others 1987). The horizontal grid resolution is 60 by 60 kilometers. At this resolution, the basin is apparent and regional mountain ranges appear as highly smoothed ridges around the basin. Mountain gaps are not resolved. The vertical resolution, although much finer than GCMs, is too coarse to capture the winter temperature inversion that frequently persists in the basin. The resulting horizontal and vertical resolution allows RegCM2 to model regional climate with reasonable accuracy. Smaller mesoscale phenomena, however, which influence many of the unique climate features of the basin, cannot be simulated accurately.

There remains much uncertainty in regional climate modeling. It is unfortunate therefore, that only one model is available. In addition, RegCM2 is nested with a GCM that initializes colder and drier than the current climate (Giorgi and others 1994). With these caveats in mind, the trends in RegCM2 output may be reasonable for general climate change in the Pacific Northwest. Magnitudes of change in the basin, however, which are dependent on smaller scale phenomena, are not well modeled by RegCM2. Table 1 lists potential changes in monthly precipitation and temperature for the Northwestern United States as depicted by the $2xCO_2$ model run of RegCM2 (Giorgi and others 1994).

Table 1—Differences between $2xCO_2$ and control run surface air temperature and precipitation for the northwestern subregion of the United States as modeled by RegCM2

Month	Precipitation	Temperature
	Percent	*Degrees °C*
1	+5	+4.4
2	+40	+5.5
3	+20	+5.2
4	+6	+2.2
5	+8	+2.5
6	+5	+4.0
7	+45	+4.0
8	+20	+4.0
9	+90	+4.8
10	+35	+3.5
11	+0	+4.5
12	+50	+4.2

Source: Giorgi and others 1994.

Columbia River Basin Climate-Change Scenario

An understanding of how local topography interacts with large-scale circulation helps to identify the controlling aspects of regional climate. Equilibrium GCMs provide basic information on large-scale changes in global circulation patterns. Transient CGCMs show patterns and magnitudes of the changing global circulation, and regional climate models can illustrate trends of potential change at smaller scales. In addition, current climate change signals help define regional magnitudes of change.

Information from all scenario tools were integrated to form a composite scenario of potential $2xCO_2$ climate-change in the basin. The magnitude of potential change in monthly precipitation, maximum temperature, and minimum temperature are discussed below and shown in table 2.

Precipitation

Because the initializing scenario of RegCM2 began drier than present conditions (Giorgi and others 1994), it is expected that output from RegCM2 overestimates possible increases in precipitation. The model-simulated jet stream, however, is weaker than observed. This also would contribute to underestimated orographic precipitation. The overestimation from dry initialization may negate the underestimation from a weak jet. Therefore, possible changes in cold-season precipitation within the basin were chosen to follow the magnitude of RegCM2 output. The month-to-month variability (especially November and January) in RegCM2 output was smoothed out, however, because it appears inconsistent with observed month-to-month trends (Ferguson, in press; Mock 1996).

Warm-season precipitation in the Northwest is significantly overestimated in RegCM2. Giorgi and others (1994) acknowledge that RegCM2 is very sensitive to local topography and claim that current observations mistakenly omit the topographic signal in convective precipitation. Thermal convection, however, largely outweighs orographic effects during late summer in the basin, and there is little evidence that summer precipitation has a clear topographic signal (Barry 1981, Mock 1996).

The seasonality of precipitation also may experience a change. Currently, most of the southeastern part of the basin experiences a slight maximum in precipitation during spring. In a $2xCO_2$ climate, the timing of maximum precipitation could shift toward summer (Finkelstein and Truppi 1991). In addition, late-summer convection over land areas could increase during a $2xCO_2$ environment (Houghton and others 1990, 1992, 1996). This may cause areas in Montana and southern Idaho, which have the strongest continental influence, to experience increased precipitation. In the climate-change scenario for the basin, it is suggested that the Pacific frontal boundary (Mitchell 1976), which bisects the basin diagonally in a line roughly coinciding with the crest line of the Blue Mountains, marks the northward extent of increased summer convective precipitation.

Table 2—A climate-change scenario for the Columbia River basin[a]

Month	Precipitation	Tmin (°C)		Tmax (°C)	
	Percent	*<1km*	*>1km*	*<1km*	*>1km*
1	+45	+3	-1	+3	-2.5
2	+40	+2	-1	+3	-2.5
3	+20	+1	-1	+2	-2
4	+5	+1	+1	+1	+1
5	+5	+1	+1	+1	+1
6	0	+1	+1	0	0
7	-5	+1	+1	0	0
8	-5[b]	+1	+1	0	0
9	+10	+1.5	+1.5	-1	-1
10	+35	+1.5	+1	0	-2
11	+40	+1	0	+1	-2
12	+50	+2	-1	+2	-2.5

[a] Percentage of changes in precipitation from current monthly values; magnitude change in minimum daily temperature (Tmin) and maximum daily temperature (Tmax) shown for elevations above and below a persistent wintertime inversion (about 1 kilometer).

[b] Convective activity over continents could increase during a $2xCO_2$ climate. In the basin, convective precipitation is most common in the southeast section (southeast Oregon, southern Idaho, and southwest Montana), so this is where a 5-percent increase in August precipitation may occur.

A modern analogue was used to show small-scale climate controls in the region during the early Holocene[1] (Mock and Bartlein 1995). The study showed decreasing late-summer precipitation over much of the basin, except the southeast where increased convective precipitation was indicated, and in northeast Washington where the passage of occasional upper level troughs caused periods of heavy precipitation.

Results from the modern analogue are consistent with the potential change scenario shown in table 2 except for the northward extent of convection and the presence of upper level troughiness in northeastern Washington. During a $2xCO_2$ climate, it has been suggested that Pacific storm track could shift northward (Held 1993). If this were the case, no increase in summer precipitation in northeast Washington would be expected. Tang and Reiter (1984) suggest that increased onshore flow through low-level gaps in the basin could limit the northward extent of the subtropical high, which is associated with convective (monsoonal) summer precipitation in the Southwestern United States. The $2xCO_2$ scenario presented here assumes that, without the influx of Pacific troughs in northern Washington, the subtropical high could follow normal patterns and extend monsoonal conditions up to the Pacific frontal boundary (Mitchell 1976), well into southern Oregon and Idaho. It is uncertain whether one summer precipitation scenario is more correct than the other.

[1] About 10,000 to 5,000 years before present.

If observed trends in basin precipitation (Ferguson, in press) are a climate-change signal, then many of the arguments for potential change in precipitation are invalid. A decrease in winter precipitation since the mid 1970s and an increase in summer precipitation since about 1960 were apparent in the observation data. This is opposite to that modeled by RegCM2 and as proposed in table 2 for the next 50 to 100 years. It may be the length of records or changes in precipitation recording equipment at observation stations that cause the discrepancy, or it could be a flaw in modeling and understanding seasonal precipitation responses to increasing greenhouse gases. Further work to resolve the differences is needed.

Temperature Trends

Winter temperature changes in the basin are distinguished by elevation. This is because a temperature inversion, where temperature is cooler near the ground and warmer aloft, persists below about 1000 meters above mean sea level during winter in the basin. The existence and strength of this inversion is dependent on snow cover. With snow, most incoming radiation is reflected away from Earth's surface so temperatures near the ground remain cool, dense, and stable, thus enhancing temperature inversions. Without snow, the exposed ground absorbs incoming radiation that reradiates to help warm near-surface air, thereby allowing it to become buoyant and well mixed, and thus minimizing temperature inversions. In the basin, a depleted winter inversion could result in the greatest warming at low elevations.

During summer, the basin topography can trap stagnant air at times, but temperature inversions are less frequent and weaker than during winter. Elevational distinction of temperature, therefore, is no longer necessary in summer.

Because RegCM2 initialized slightly colder than current climate (Giorgi and others 1994), potential increases shown in table 1 may be too large. Also, the basin is in the mid latitudes and near moderating ocean currents. Potential change in regional temperatures, therefore, should be moderated and close to global averages, with annual average increases of about 1 °C. After the previous discussion, most of the potential change could be expected at lower elevations during winter, where up to 3 °C warming in monthly averaged surface temperatures may be possible.

At elevations above the basin inversion, the proposed climate-change scenario suggests some cooling. This is highly uncertain because few climate models have shown anything but warming in this region under a 2xCO_2 climate. In addition, analysis of long-period weather records indicates an overall warming trend in the Pacific Northwest (Karl and others 1990). Most long-period weather records in the basin, however, are at low elevations where increases are suggested (table 2). The assumption of cooling at high elevations is based on a report indicating that increased cloudiness in the Western states causes general cooling, opposite to that observed in the Eastern states.[2] Also, Mock and Bartlein (1995) suggest that decreases in temperatures around the eastern Cascade Range and upper Columbia and Snake River plateaus may be possible if a stronger than normal onshore (marine) flow were to occur.

Maximum and Minimum Temperature

Some evidence shows that the range between daily maximum and daily minimum temperature is decreasing (Ferguson, in press; Karl and others 1993). Most of the reduction in daily temperature range (DTR) seems to be caused by increasing daily minimum temperatures that could be associated with an increase in cloud cover. Cloud cover in the basin could have a complex changing pattern. At low elevations during winter, if the winter inversion were to decrease, so too would associated fog and low clouds. The basin climate-change scenario, therefore, assumes that the biggest decreases in daily temperature range occur during summer and early fall. A slight increase in DTR is added to the basin climate-change scenario during February and March, when snowcover changes could be most dramatic. Although Karl's group found little correlation between snow cover and daily temperature range, Cao and others (1992) suggest that reduction of snow cover will increase DTR.

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[2] Tangborn, W. [Date unknown] Climate-change signal detected with a two-component temperature analysis. 14 p. Unpublished report. On file with: HyMet, Inc., 2366 Eastlake Avenue East, Seattle, WA 98102.

Suggestions For Further Work

Understanding aspects of our environment that control the heterogeneity of climate in the basin is key to interpreting model results and anticipating potential change. New methods of analyzing existing observation data and proxy climate data are needed to evaluate the effects of topographic elevation and orientation, as well as the influence and interaction of mesoscale and synoptic-scale weather features.

Much work is needed to generate realistic climate scenarios in mountainous regions where few data are available and where small-scale features of topography can affect larger scale patterns in regional climate. Precipitation observation sites in the western mountains usually are spaced 20 to 60 kilometers apart (Ferguson and others 1990). Observations of other parameters have much coarser site spacings.

The transition-type climate of the basin and the high degree of topographically controlled flow patterns necessitates physical modeling of many important atmospheric parameters. Three-dimensional physical models currently require parallel-linked processors (mainframes and multiple RISC-based workstations) to accurately model climate over large domains and long time series. Categories of large-scale patterns, however, can be generated to demonstrate means and extremes of climate. These categories can be used as boundary conditions for nesting mesoscale models that illustrate local and regional response to large-scale climate patterns.

Stochastic techniques for generating climate scenarios remain valid in regions of complex terrain if they include topographic parameters (Daly and others 1994, Thornton and Running 1996). Current models, however, need to be improved to accurately represent climate in remote mountain areas with scarce climate observations, like many places around the basin.

Conclusion

This work rationalized the best use of available climate scenario tools to generate a quantitative description of potential climate change in the basin. These potential change values, of monthly precipitation, minimum monthly averaged temperature, and maximum monthly averaged temperature, are summarized in table 2. It should be emphasized that there is much uncertainty in climate modeling.

Although the climate-change scenario presented here is unprecedented in human history, there are indications of similarities to ancient climate. For example, investigations of flood-plain deposits along the Columbia River show alternating periods of intense flooding and quiescence during the Holocene[3] thermal maximum (Chatters and Hoover 1992). The conditions of intense flooding coincided with moderate increases in winter precipitation and winter warming, similar to conditions possible under a $2xCO_2$ climate-change scenario.

[3] About 9,000 to 2,000 years before present.

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This work describes the method used to generate a climate-change scenario for the Columbia River basin. The scenario considers climate patterns that may change if the atmospheric concentration of carbon dioxide (CO_2), or its greenhouse gas equivalent, were to double over pre-Industrial Revolution values. Given the current rate of increase in atmospheric CO_2 concentration, doubling could occur within the next 50 to 100 years.

The Columbia River basin is in a transition climate zone between predominating maritime to the west, arctic to the north, and continental to the east. Consequently, it is difficult to characterize through means and averages. Therefore, many of the current stochastic methods for developing climate-change scenarios cannot directly apply to the basin. To circumvent this problem, a composite approach was taken to generate a climate scenario that considers knowledge of current regional climate controls, available output from general circulation and regional climate models, and observed changes in climate.

The resulting climate-change scenario suggests that precipitation could increase substantially during winter (+20 to +50 percent) and moderately during spring and autumn (+5 to +35 percent). A slight decrease (0 to -5 percent) in summer precipitation is possible, except for the southeastern portions of the basin that may experience an increase in convective precipitation (+5 percent).

Low-elevation (<1 kilometer) temperatures throughout the year may increase 1 to 3 °C, with greatest increases during winter. This amount of temperature change is possible because of an expected loss of low-elevation snow cover. At high elevations, increased cloud cover could cause average temperatures to decrease during winter but be synchronized with possible warming at low elevations during summer. The diurnal range of temperature could decrease, especially in summer and autumn.

Keywords: Climate, climate change, climate scenario, Columbia River basin, Pacific Northwest, global warming, general circulation model, regional climate model, global change, global climate, greenhouse gas.

Pacific Northwest Research Station
333 S.W. First Avenue
P.O. Box 3890
Portland, Oregon 97208-3890